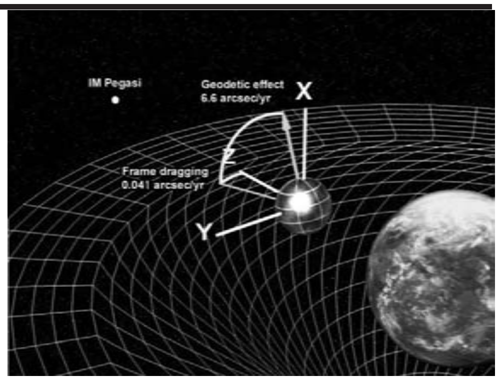
National Aeronautics and
Space Administration

The Gravity Probe B Mission

When Einstein produced his revolutionary **Theory of General Relativity in 1916**, perhaps he was able to imagine what curved spacetime looked like by simply looking at the stars and consulting his equations. The evidence for his theory lay in the elegance and congruence of the ideas.

As the 20th century progressed, scientists hoped to test Einstein's theory with experimental evidence. Results from concrete experiments were needed to confirm or revise Einstein's theory of the structure of the universe. But could one actually "see" spacetime? How could one examine the invisible, intangible structure of the universe?

In 1960, Stanford University physicist Leonard Schiff (and, independently, Defense Department physicist George Pugh) suggested that the presence of local spacetime could be "seen" by using **gyroscopes**. If one could float a gyroscope in Earth orbit, the gyroscope, given its natural inertia, would remain fixed in spacetime. If the spacetime itself moved or was curved, the gyroscope would turn with it.



This is how Gravity Probe B works:

1. **A gyroscope and telescope** are in a satellite which is flying in a **polar orbit** 400 miles (640 km) above the Earth.

2. The telescope and the gyroscope's spin axis are **perfectly aligned**, and both were pointed at a distant star (IM Pegasi).

3. Throughout a year of orbit, the telescope will remain fixed on a distant star. The spinning gyroscope, which is floating in a vacuum within the satellite, is free to drift with any changes in the local spacetime frame.

4. According to Einstein's theory, the gyroscope should turn in two directions simultaneously. As it travels through curved spacetime, it will turn slightly along one axis. As "frame-dragging" occurs, it will also turn slightly along a perpendicular axis.

5. Schiff calculated that at a 400-mile altitude, spacetime curvature would turn the gyroscope **6.6 arcseconds per year** in one direction, and the "frame-dragging" will turn it **.041 arcseconds per year** in a perpendicular direction.

During the 14-month mission, delicate sensors will measure the angle that opens up between where the telescope is pointing and where the gyroscope is pointing. The challenge for Gravity Probe B since 1960 has been to invent, develop and build the technology that could measure these minuscule angles in the extreme environment of space and make Schiff's vision a real test of Einstein's theory. In April 2004, the ultimate mission began.

For more information, comments or questions, contact GP-B at www@relgyro.stanford.edu or visit http://einstein.stanford.edu/

GRAVITY PROBE B

THE RELATIVITY MISSION

National Aeronautics and
Space Administration

Gravity Probe B Launches!
April 20, 2004

At 9:57:24 am (PDT) on Tuesday, April 20, 2004, the Gravity Probe B spacecraft rose spectacularly off the launch pad from Vandenberg Air Force Base in south-central California. Flying through the speed of sound in less than thirty seconds, the rocket quickly shot the satellite up to fifty-five miles in the atmosphere. All systems and data checked out and within an hour, the GP-B satellite emerged from the nose cone of the rocket.

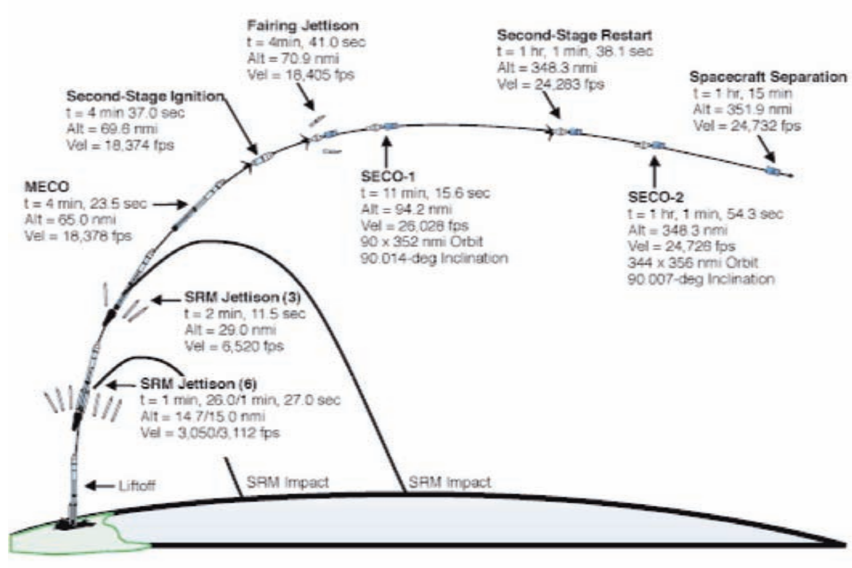
At one hour eleven minutes, the spacecraft's solar arrays deployed, and shortly thereafter, the on-board cameras treated all viewers, via NASA-TV, to the extraordinary sight of the separation of the spacecraft from the second stage rocket, with a portion of the Earth illuminated in the background. The Boeing Delta II 7920-10 rocket hit the bull's eye in placing the spacecraft in its target polar circular orbit, 400 miles (650 km) above the Earth.

To see when the satellite is visible from your location, you can track the GP-B satellite on the Web using NASA's J-Pass satellite tracking application at: http://science.nasa.gov/realtime/JPass/

The launch window for GP-B was only one second long each day from April 19-21, 2004. On the first day, the launch countdown reached t-3 minutes before scrubbing due to lack of information about high-altitude winds. On the second day, the launch was about four minutes earlier due to the Earth's progression around the Sun each day. The rocket was launched due south over the Pacific Ocean and towards the South Pole where it began its circular polar orbits.

The spacecraft is being controlled from the Gravity Probe B Mission Operations Center, located here at Stanford University. The Initialization & Orbit Checkout (IOC) phase of the Gravity Probe B mission lasted 120 days, after which GP-B entered the 10-month science data collection phase. This will be followed by a month-long final calibration of the science instrument assembly.

Gravity Probe B Flight Profile



ABOUT THE IMAGE
(clockwise from left)

1) The Delta II rocket carrying the GP-B satellite soars over the California coast.

2) The GP-B spacecraft just after separation with the Earth illuminated in the background.

3) The Delta II rocket with the NASA, GP-B, Boeing and VAFB decals at the moment of liftoff.

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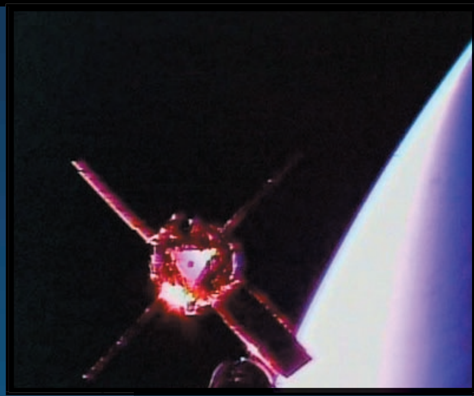
Gravity Probe B Launches!
April 20, 2004



National Aeronautics and
Space Administration

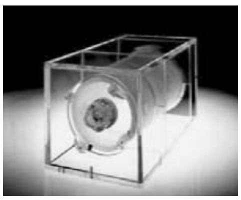
The Gravity Probe B Satellite

The Gravity Probe B satellite is an amazing piece of equipment, finally completed in 2003 after four decades of development and construction. From its largest to smallest parts, it is filled with cutting-edge technology and materials, many of which were invented specifically for the Gravity Probe B mission.

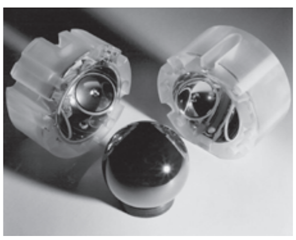
The main body of the GP-B structure is the nine-foot tall dewar, a 650-gallon thermos that insulates the science instrument from solar radiation. It can maintain a stable supercooled environment for eighteen months by using a "porous plug" to remove evaporating helium gas from the helium liquid in its superfluid state. Some important equipment is attached outside the dewar, including the telescope's sunshield, the solar array panels, and the helium gas thrusters. But the technological heart of Gravity Probe B resides in the Science Instrument Assembly (SIA) inside the dewar.

The SIA

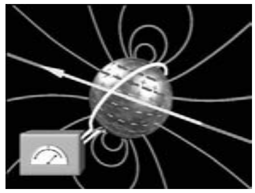
A 14-inch fused quartz telescope, with a 5.5-inch aperture, is able to pinpoint the center of a distant star (IM Pegasus) to within 0.1 milliarcseconds.



Bonded to the rear of the telescope is a fused quartz block containing the centerpieces of the GP-B mission, four fused quartz gyroscopes. These 1.5-inch gyroscopes spin at 4,000 rpm inside housings arely larger than the gyroscopes. They are the most spherical objects in the world, polished to within 0.01 microns of perfect sphericity.



Within the fused quartz block are superconducting loops and SQUID's (Superconducting QUantum Interference Devices) to monitor magnetic fields around the gyroscopes. The quartz block also contains electronics to keep the gyroscopes levitated and centered within the housings, and a gas transport system that spun up the gyroscopes at the start of the mission and maintains a near-perfect vacuum throughout the mission.



A lead "bag" surrounds the SIA to accomplish two goals: 1) to protect it from any interfering magnetic fields, and 2) to create a magnetic field vacuum inside the SIA to <10^{-7} gauss. The entire quartz block and telescope are constructed of several ultra-pure quartz sections, attached through "molecular adhesion" to limit gravitational sag. The SIA is also surrounded by supercooled liquid helium which keeps the probe at 1.8 Kelvin (-271.4˚C). This allows the superconducting materials to function and further stabilize all the quartz materials.

Before Gravity Probe B was completely integrated, each component went through years of testing and construction. Some parts even had to be de-constructed and rebuilt. The entire probe was assembled in a Class-10 clean room, as any particles larger than a single micron would disrupt the precise structure.

Using this sophisticated instrument and satellite, Gravity Probe B is orbiting the Earth for 14 months, examining the shape and motion of local spacetime in an attempt to make the most precise test of Einstein's general theory of relativity ever attempted.

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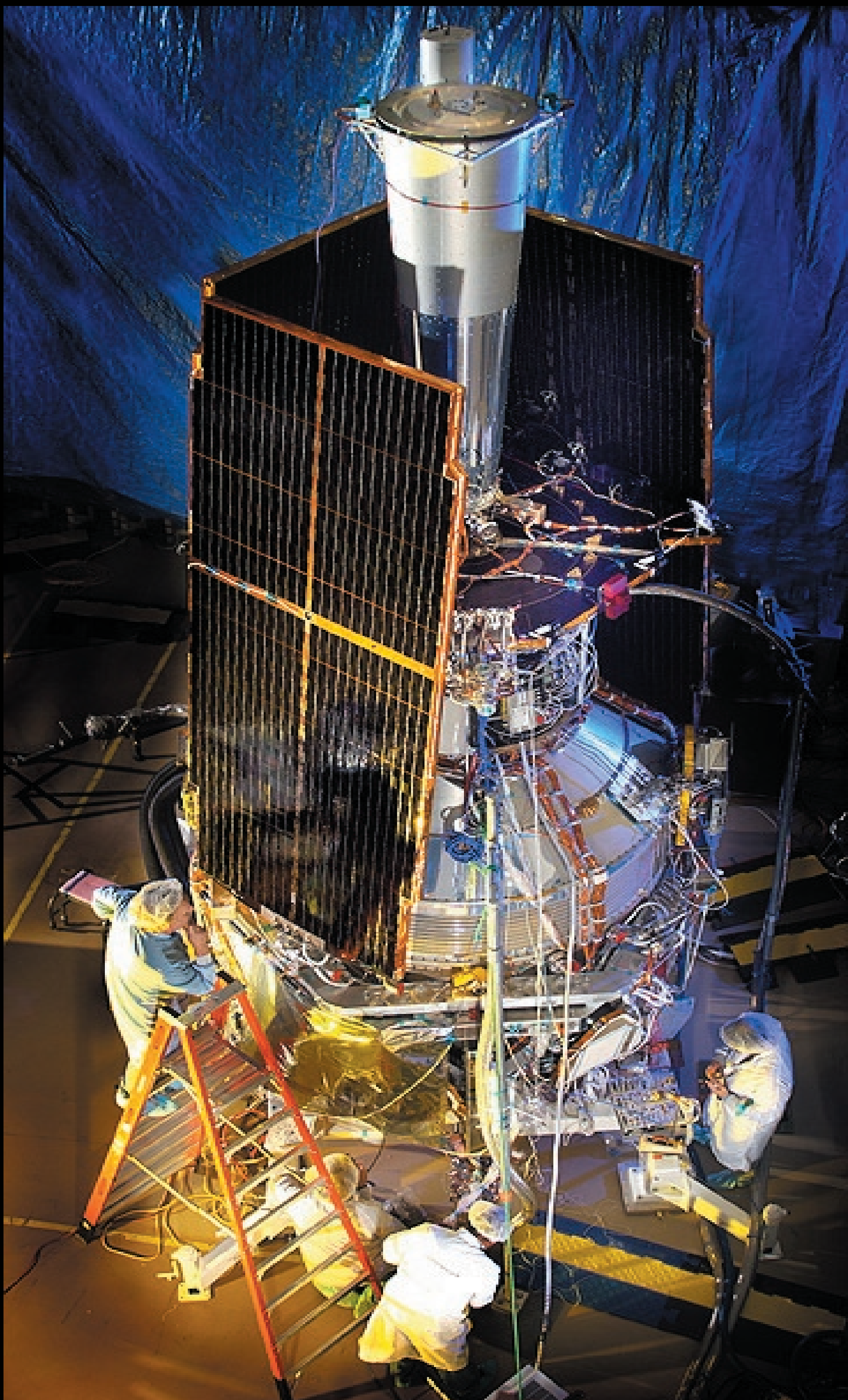
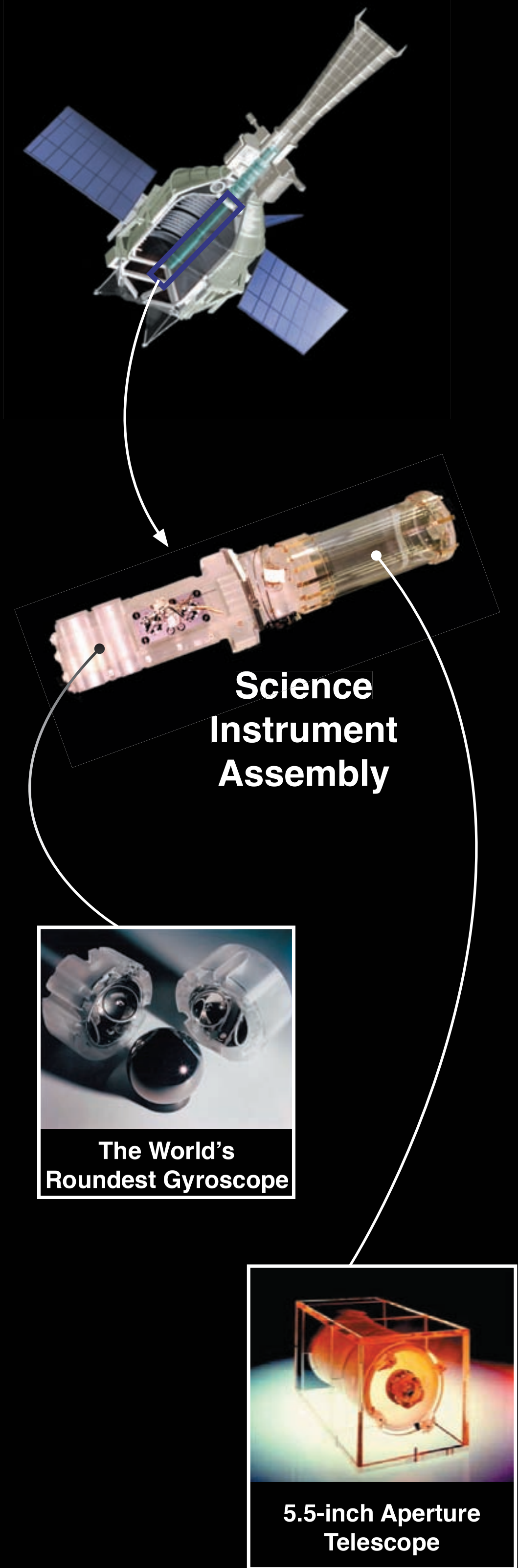
National Aeronautics and
Space Administration

The Gravity Probe B Satellite





National Aeronautics and
Space Administration

Keeping Our Cool Near Absolute Zero

Gravity Probe B

One of the greatest technical challenges for Gravity Probe B is to keep its science instrument constantly supercooled. For the relativity experiment to operate properly, the science instrument must be kept at **1.8 kelvin (-271.4 degrees celsius)** for at least one year. Key portions of the science instrument must be maintained at a constant temperature to within five millionths of a degree celsius (+/- 0.000005˚C).

Initially, the science instrument is cooled by placing it in a **dewar,** a special 645-gallon “thermos”, filled with superfluid liquid helium. The nine-foot tall dewar is the main structure of the satellite itself. Like all thermos bottles, the inside of the dewar has a vacuum, which limits the amount of heat penetrating through the outside wall into the inner chamber containing the science instrument.

However, once the GP-B satellite is in polar orbit above the Earth, keeping it supercooled becomes significantly harder. During the year, it is exposed to the Sun’s light for irregular amounts of time depending on the where the Earth is in its orbit around the Sun. Several other systems had to be developed to assist the dewar in maintaining the supercooled liquid helium.

Structurally, the dewar has multi-layer insulation and vapor-cooled sheilds. The multi-layer insulation has multiple reflective surfaces in the vacuum space to cut down on any penetrating radiation. The vapor-cooled shields provide metal barriers, suitably spaced, that are cooled by the escaping helium gas.

One of the most critical devices for stabilizing the GP-B temperature is a **“porous plug”**, which was invented at Stanford and engineered for space at NASA Marshall Space Flight Center and the Jet Propulsion Laboratory. This plug has the unique ability to allow helium gas to escape while containing the liquid helium. It acts like a sponge on the gas, “wicking” it out of the dewar.

Releasing the helium gas aids the experiment in three ways. First, it limits the “bump-boiling” effect. Despite all the thermal protection provided, some liquid helium will gradually heat up and become helium gas. If this gas stayed in the dewar its atoms would “bump” into the liquid atoms and transfer heat energy, causing more liquid to “boil” which would create more gas which would then heat more liquid and so on. By releasing this gas, the “bump-boiling” process is slowed considerably.

Second, the evaporating helium provides its own kind of refrigeration. As the helium gas escapes from the dewar, it carries heat energy with it. The liquid helium in the dewar loses this energy and becomes colder still. You can feel this effect when alcohol or liquid evaporates off your skin. It draws heat energy with it, leaving your skin a tiny bit cooler than before.

Third, the escaping helium gas is directed through several positioning valves to control the satellite’s position. To turn the satellite, the gas flow is slightly reduced or increased through the appropriate side. If the porous plug was not allowing the helium gas to escape, the satellite could not maintain its precise positioning.

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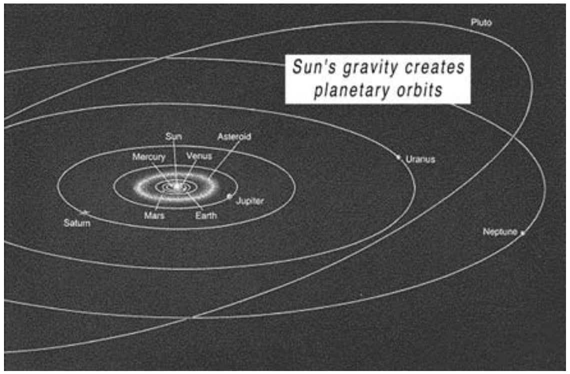
Keeping Our Cool Near Absolute Zero

Newton's Gravity or Curved Spacetime?

According to Newton's theory of gravity (1687), all masses pull on each other with an invisible force called "gravity". This force is an inherent property of matter, and is directly proportional to an object's mass. In our solar system, the Sun reaches out across enormous distances and pulls smaller masses, like planets, comets, and asteroids, into orbit around it using its force of gravity.

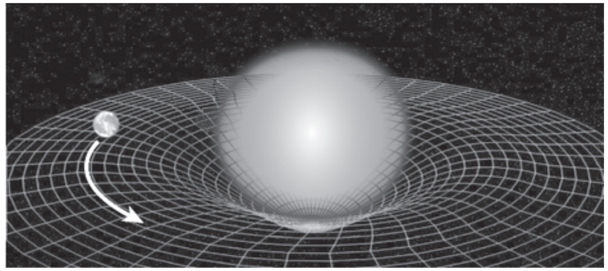


In the early 20th century, Einstein discovered a contradiction between Newton's theory of gravity and Einstein's theory of special relativity (1905). In special relativity, the speed of light is the speed limit of all energy in the universe. No matter what kind of energy it is, it cannot transmit across the universe any faster than 299,792 km/sec. Yet Newton's theory assumed that the Sun's force of gravity is *instantaneously* transmitted to the planets, at a speed much faster than the speed of light. Was gravity unique in its ability to fly across the universe, or did masses react to each other for a different reason?

In 1916, Einstein published his theory of general relativity, which transformed space from the Newtonian idea of vast emptiness to an ephemeral fabric of spacetime, which "grips" matter and directs its course through the universe. The spacetime fabric spans the entire universe and is intimately connected to all the matter and energy within it.

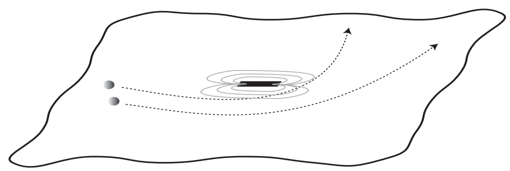
How does this change in thinking explain the motion of the planets, or the orbits of the moon and satellites around Earth? Theoretically, when a mass sits in this spacetime fabric, it will deform the fabric itself, changing the shape of space and altering the passage of time around it.

In the case of the Sun, the spacetime fabric would curve around it, creating a "dip" in spacetime. As the planets (and comets and asteroids) travel across the spacetime fabric, they would respond to this dip and follow the curve



in spacetime and travel around and around the Sun. As long as they never slow down, the planets would maintain regular orbits around the Sun, neither spiraling in toward it nor flying off into outer space.

To create a simple model of this idea, place a heavy weight in the center of a suspended bedsheet. Roll some small balls across the sheet at different points and observe how they curve in toward the central weight.



The balls are not "pulled" in by the mass's gravity; they are simply following the curve in spacetime caused by the mass's presence.

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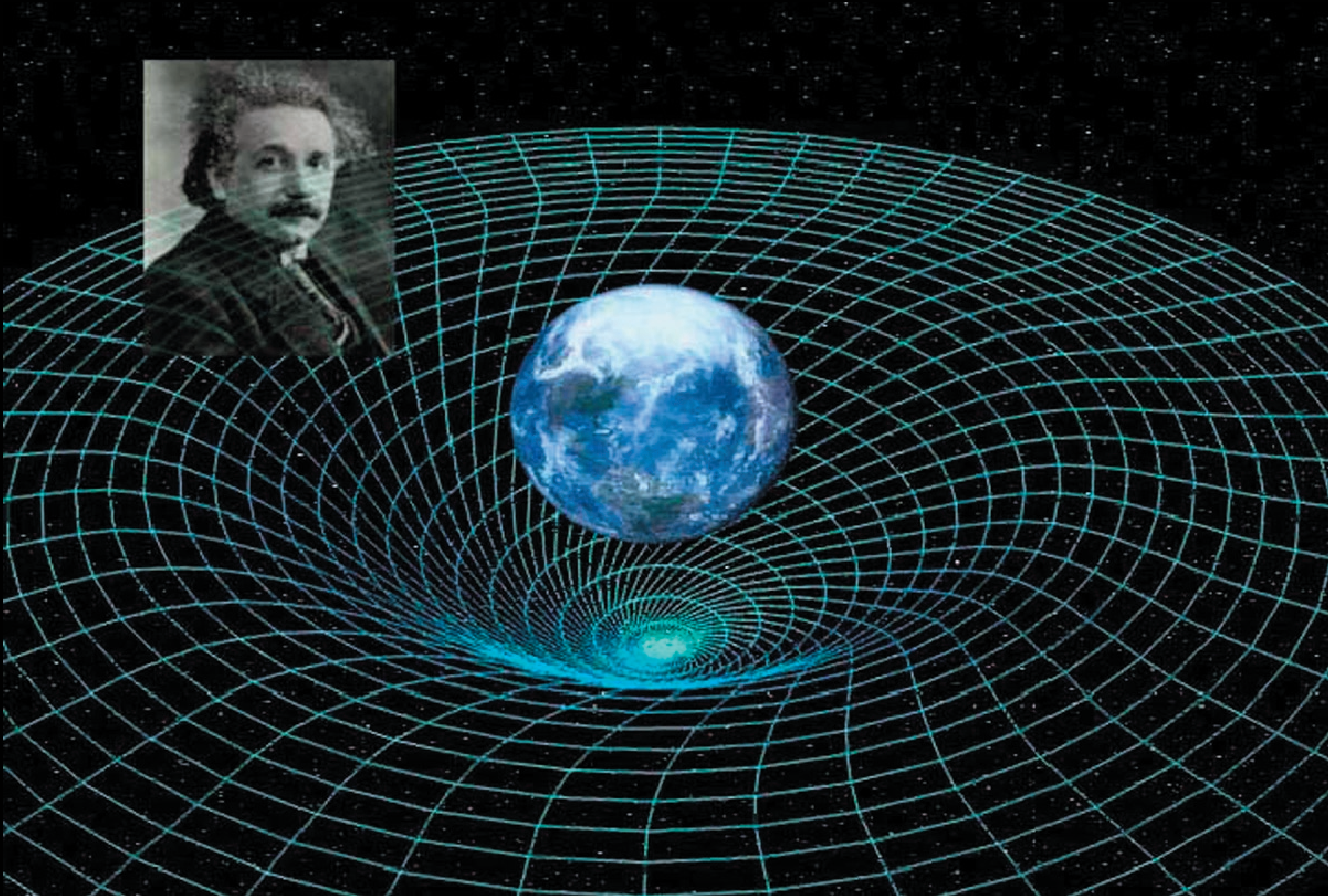
NASA

Newton’s Gravity or Curved Spacetime?

Gravity ProBe



“Frame-Dragging” in Local Spacetime

In 1918, just two years after Einstein presented his general theory of relativity to the world, two other physicists, Josef Lense and Hans Thirring, predicted that masses in spacetime could deform spacetime in more than one way. Masses will not only “curve” the structure of spacetime around them, but also they will “twist” local spacetime if the mass is rotating.

This predicted effect was called “frame-dragging” to illustrate how a rotating planet will “drag” the local frame of reference around it. This “twisting” would alter measurements of distance, time, and direction in local spacetime.

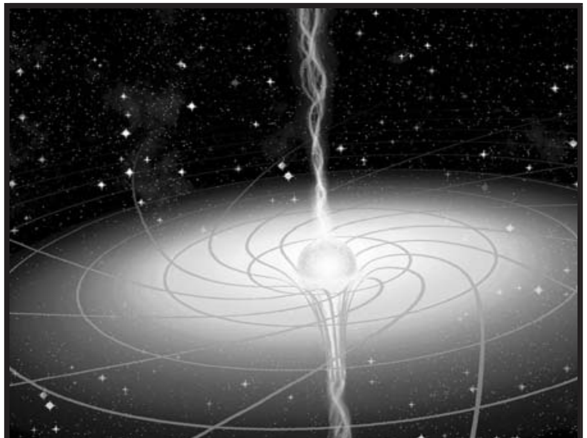
One way to visualize this effect is to place a small ball in a bowl of honey. Add a drop of food coloring near the ball. Now, spin the ball quickly and notice that the honey turns with it. The honey that is closer to the ball is pulled around more than the honey that is farther away from the ball. Notice also that the food coloring, or anything else floating in the honey, is pulled around, as well.

The spinning ball represents our Earth and the honey represents spacetime. According to the predictions of Lense and Thirring, as our Earth rotates, it should drag local spactime around with it. This frame-dragging effect should be most noticeable close to our rotating Earth, fading away almost completely as we move farther away.

The predicted frame dragging effect around a planet with the mass and size of our Earth, as measured by the Gravity Probe B gyroscopes, is very, very small—only 42 milliarcseconds of angle over the course of a year.

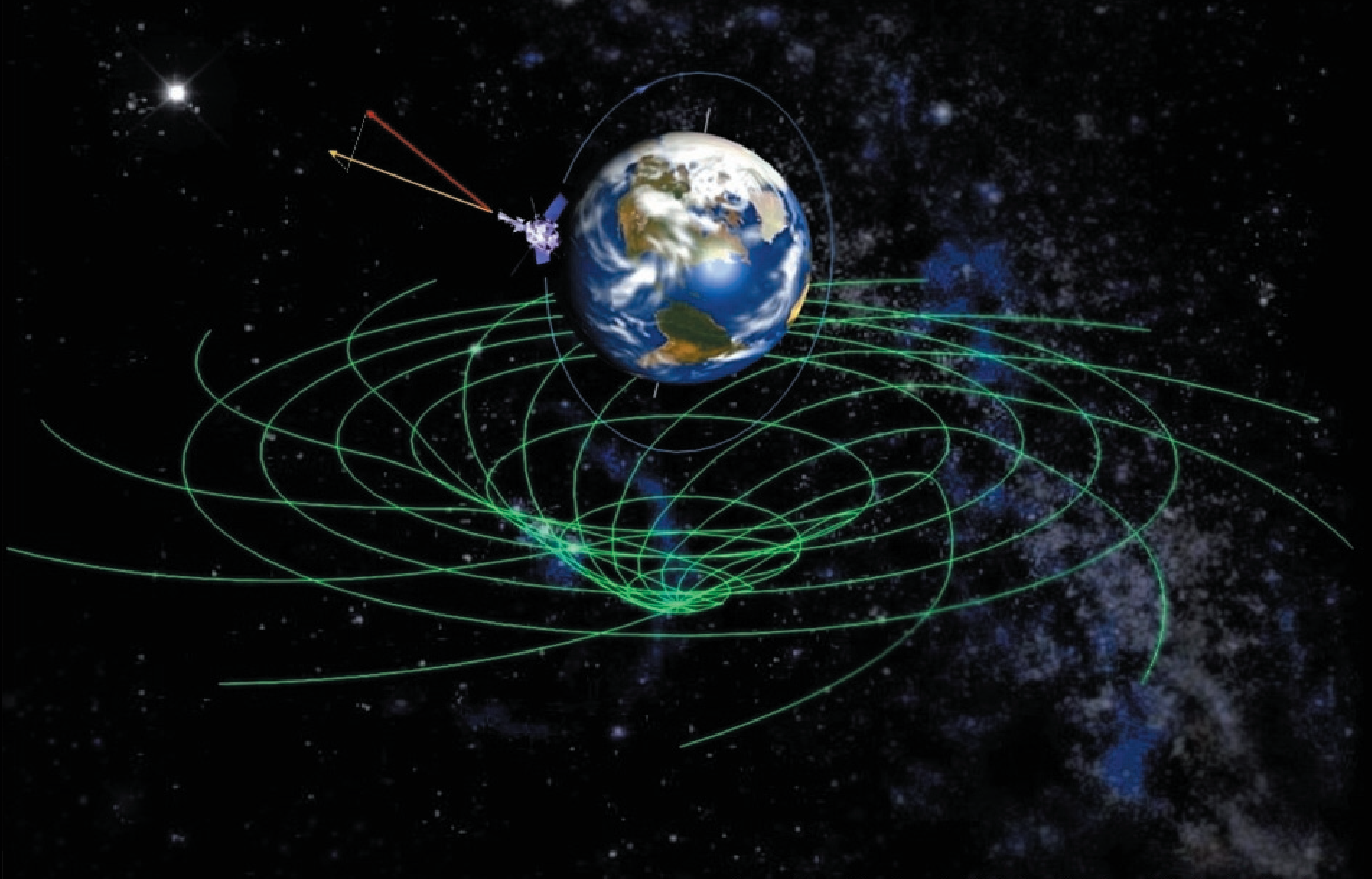
How small an angle is 42 milliarcseconds? One milliarcsecond is 1/1,000 of an arcsecond, and there are 3,600 arcseconds in a single angular degree. 42 milliarcseconds is approximately equivalent to the width of a human hair as seen from 1/4 mile away!

It takes an extremely precise instrument to measure such a tiny angle—which is why the frame dragging effect has never been measured before. The Earth is an rather small body in the scale of the universe, so frame-dragging is but a whisper in this realm. However, in the vicinity of black holes and other massive bodies, scientists believe that the effects of frame dragging are enormous, and that frame dragging may be responsible for the power generation in some of the most explosive objects in the universe.



In this hypothetical illustration, a rotating black hole drags spacetime around with it. Ultra-powerful jets of energy shoot out above and below the spinning black hole along its spin axis. Scientists believe that frame-dragging may be responsible for this phenomenon. While the energy jets have not been seen in black holes, they have been spotted emerging from distant quasars.

“Frame-Dragging” in Local Spacetime



c. James Overduin, Pancho & Evelyn Eekels and Katherine Stephenson

National Aeronautics and Space Administration

The World's Roundest Gyroscopes

In order for Gravity Probe B to measure any "twist" or curvature of local spacetime, it must use a gyroscope that is nearly perfect – one that will not wobble or drift more than one-hundred-billionth of a degree in an hour while it is spinning (0.00 000 000 001). It must be this precise because the predicted twist of local spacetime is smaller than one-millionth of a degree each year!

A nearly-perfect gyroscope must be nearly perfect in two ways: sphericity and homogeneity. Every point on its surface must be exactly the same distance from the center (a perfect sphere), and its structure must be identical from one side to the other (homogenous).

After years of research and development, Gravity Probe B produced just such a gyroscope. It is a 1.5-inch sphere of fused quartz, polished and "lapped" to within a few atomic layers of perfect sphericity. A scan of its surface shows that only *.01 microns* separate the highest point from the lowest point. Transform the gyroscope into the size of the Earth and its highest mountains and deepest ocean trenches would be *a mere sixteen feet apart*! It is the most spherical object ever made, and more spherical than most things in the universe, rivaled only by extremely dense neutron stars!

Inside, the gyroscope is solid fused quartz. The quartz was chosen from a mine in Brazil and shipped to a refining plant in Germany. In Germany, it was separated, smelted, molded, then smelted and molded again, gradually removing its impurities. By the time it reached Gravity Probe B, the fused quartz blocks were some of the purest materials in the world, setting the ISO standard for material homogeneity (International Standards Organization).

The gyroscopes were ground and polished from only the purest of pure quatrz. When examined using a unique refractive comparison method, the gyroscope's quartz structure was identical throughout to within two parts in a million. That is like having every person in a city of 1,000,000 people be your identical twin except for two!

ABOUT THE IMAGE

Gravity Probe B gyroscope (rotor) with quartz housing halves. Each quartz rotor is coated with niobium, a superconducting metal. Inside each housing, three electrodes electrically suspend the gyroscope allowing it to spin freely at 4,000 rpm. Channels are cut in the quartz housing to allow helium gas to start the rotor spinning. A wire loop embedded in the housing connects to an external SQUID to detect any change in direction of the gyroscope's axis.

FAST FACTS

Gyro Size
1.5 inches of fused quartz

Sphericity
< 40 atomic layers from perfect

Quartz Purity
Within 2 parts per million

Gyro Spin Rate
~4,000 rpm

Gyro Drift Rate
$< 10^{-12}$ degrees/hour

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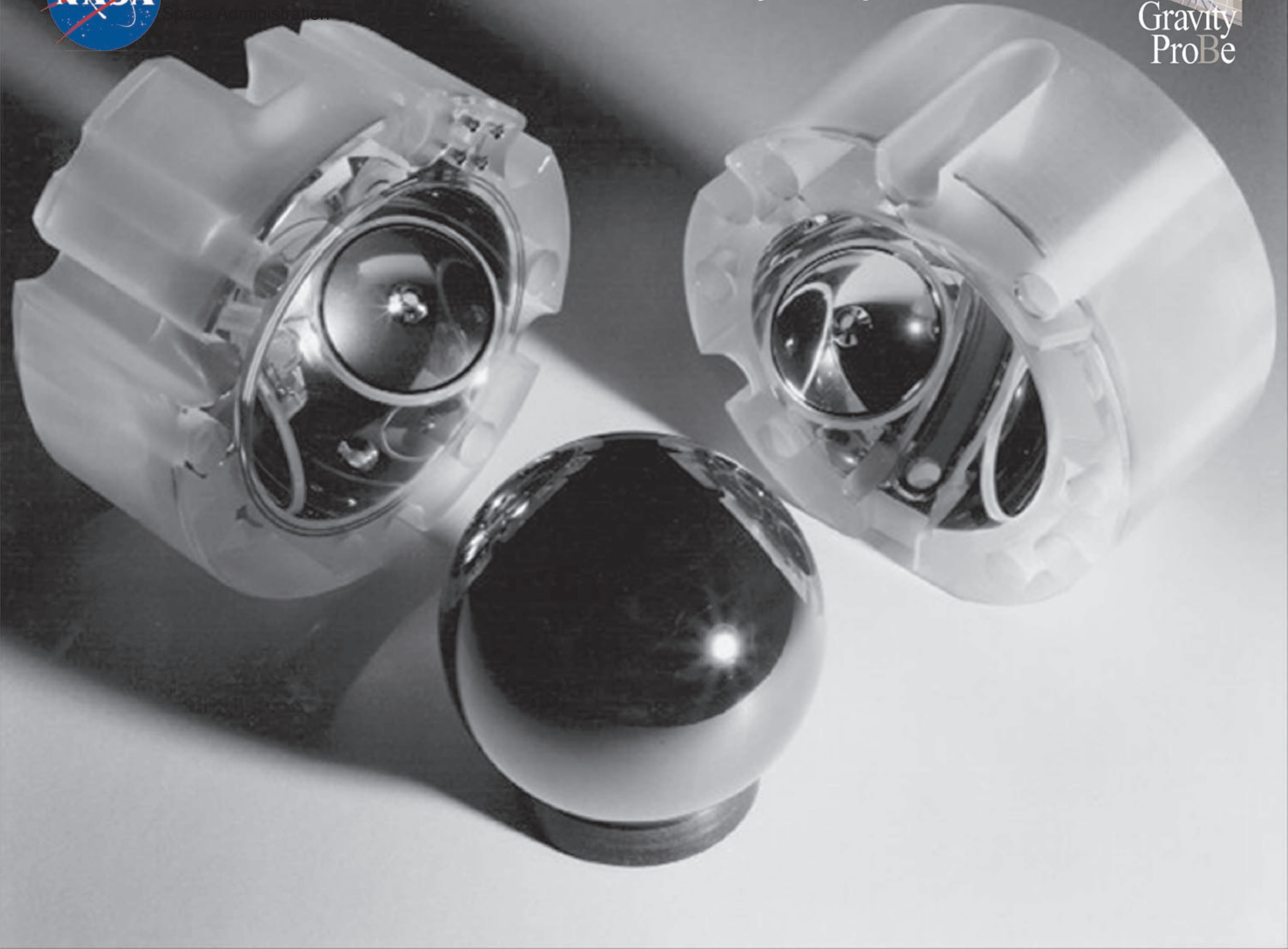
The World's Roundest Gyroscopes



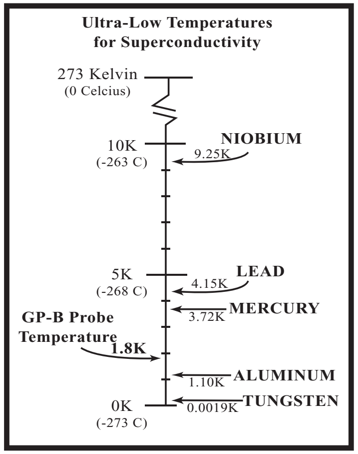
National Aeronautics and Space Administration

Using Superconductivity to "See" a Spin Axis

Gravity Probe B's ultraspherical spinning gyroscope acts as a pointer floating in spacetime. The gyroscope's spin axis was aligned with a distant star at the beginning of the mission. After one year of orbit, scientists predict that the gyroscope, floating freely above the Earth, will turn slightly as local spacetime twists slightly (see "Frame-Dragging" card). The predicted amount of turn is extremely small (< 0.002% of a degree), which means that the gyroscope must be extremely stable while it is spinning (~10^{-12} degrees of drift per hour).

Given this need for an ultra-stable spin, how could GP-B measure -- to 0.5 milliarcseconds -- the orientation of the spin axis of this perfect unmarked sphere, and do so without disturbing its perfectly balanced rotation?

The answer came from an unexpected source -- **superconductivity**. When some metals are supercooled **near absolute zero** (0 kelvin, -273.15° celsius), they have the remarkable ability to conduct electricity without resistance; i.e., they become "superconductors". Another unique property of these superconducting metals is that they produce a magnetic field when the metal is spinning. The central axis of this magnetic field is exactly aligned with the spin axis of the rotating metal. This phenomenom is known as **the "London moment"**, named after Fritz London who predicted its existence in 1948. This was experimentally verified in 1963.



Gravity Probe B applied the London moment phenomenon to its experiment by coating its four fused quartz gyroscopes with a sliver-thin layer of niobium (1270 nanometers thick), a superconducting metal. As predicted by the "London moment", when each gyroscope spins, the superconducting niobium layer generates a magnetic field around the gyroscope. Within the niobium layer, the metal's positive charges spin with the gyroscope, but its electrons are "slippery" and lag behind. This creates a charge difference, which creates a magnetic field. The axis of this magnetic field is exactly aligned with the spin axis of the gyroscope.

To know which direction the gyroscope is pointing, GP-B simply monitors the orientation of this magnetic field. A thin superconducting metal loop which is connected to an external **SQUID** (a Superconducting QUantum Interference Device) encircles the gyroscope. If and when the gyro tilts, the magnetic field tilts with it, minutely changing the orientation of the magnetic field. The magnetic field affects the current in the superconducting loop which the SQUID senses. The SQUID is so sensitive that it can detect a field change of 5 x 10^{-14} gauss (1/10,000,000,000,000 of the Earth's magnetic field), corresponding to a gyro tilt of 0.1 milliarcsecond.

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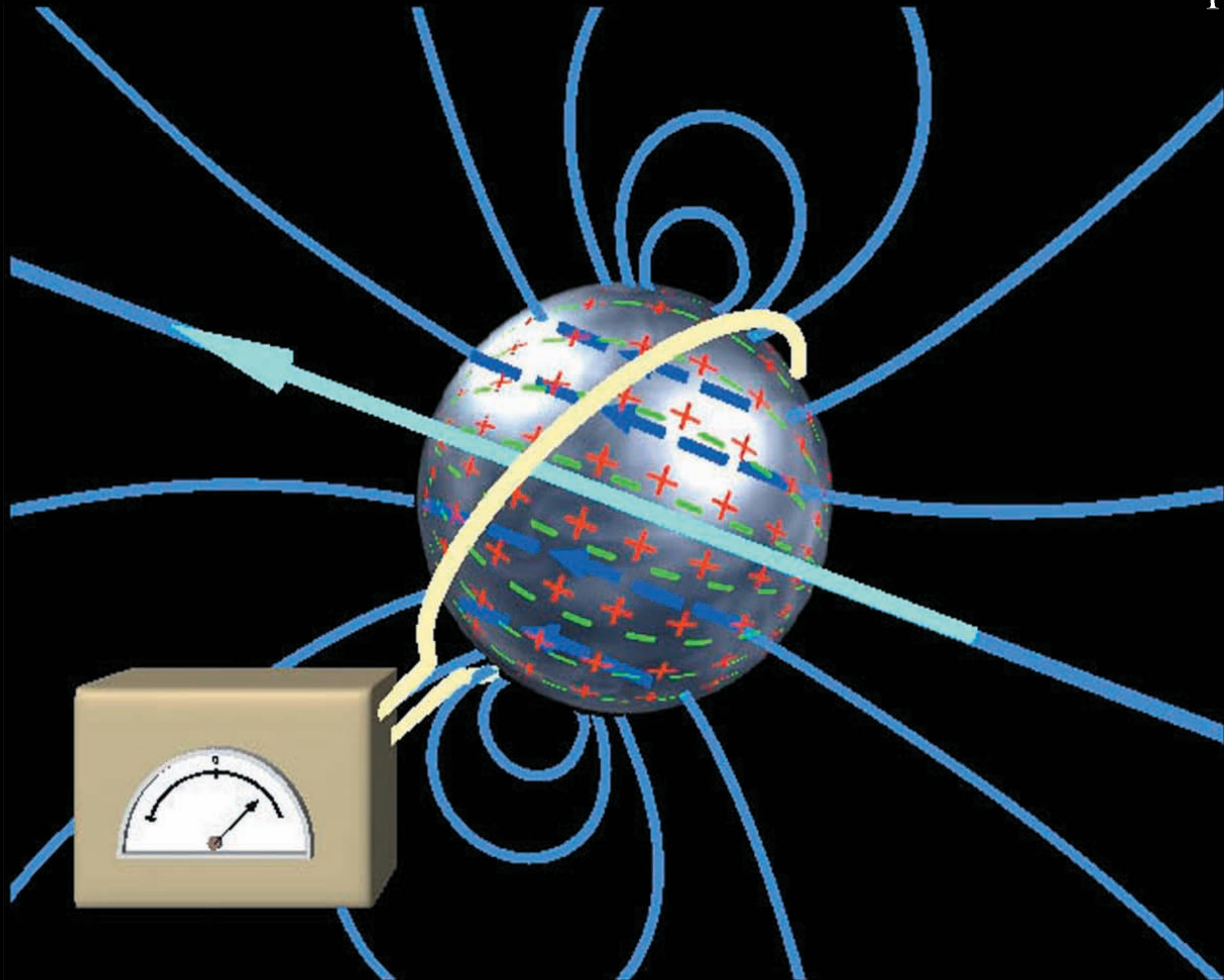
Using Superconductivity to “See” a Spin Axis



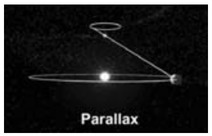
Focusing On the Guide Star

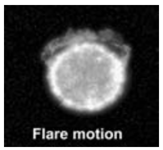
National Aeronautics and Space Administration

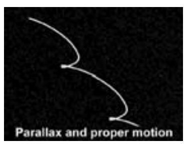
While the stars in the sky may appear to be fixed points of light, they are anything but stable objects. They wander around the sky relative to other objects, and as their light travels to Earth, it diffracts, or scatters, as it passes through the universe.

This instability and fuzziness creates significant problems for Gravity Probe B. For the experiment to work, GP-B must have an extremely stable, distant reference point at which to aim its telescope and gyroscope. If the guide star that we choose moves more than 0.1 milliarcsecond, GP-B cannot trust the star to be steady enough to measure the minute effects of local spacetime on the GP-B gyroscope.

Gravity Probe B examined many stars as possible candidates before settling on IM Pegasi as the most stable star they could use. But even IM Pegasi is not very still. This star has four unsettling motions: its proper motion, orbit perturbations from a binary star, annual parallax from the Earth's orbit, and star flares.

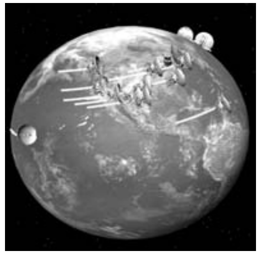

Parallax


Flare motion

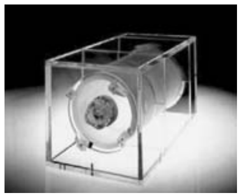

Parallax and proper motion


All four motions combined

To account for all these motions, IM Pegasi is monitored by a sophisticated worldwide system of radio telescopes operating in conjunction with each other. Telescopes from New Mexico to Australia to Germany focus on the guide star and map its movements as if one telescope the size of the Earth was focused on the star. In addition, the motions of the guide star are compared to an extremely distant quasar, an exceptionally still and "loud" object in the sky. The quasar emits powerful radio waves which make it easier to pinpoint in the sky.

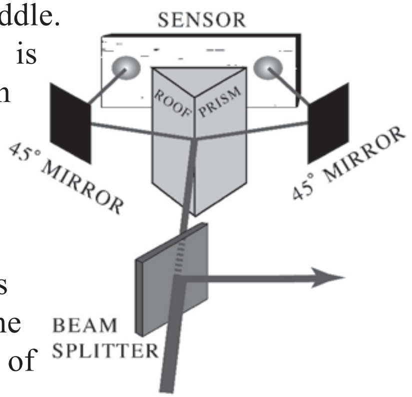


The second issue is finding the exact center of a star whose light is widely diffracted. GP-B solves this by using a sophisticated optical telescope only fourteen inches long. Diffraction spreads the star's image to a diameter of 1,400 milliarcseconds, corresponding to a focused image 0.001 inch across. Locating the star's center to 0.1 milliarcseconds means finding the image's optical center to one ten-millionth of an inch -- a formidable task.



GP-B accomplishes this task by focusing the starlight in the "lightbox" at the telescope's front end, and passing it through a beam-splitter (a half-silvered mirror). The beam-splitter forms two separate images, each of which falls on a roof-prism (a prism shaped like a peaked rooftop). The prism slices the star's image into two half-disks, which are directed to hit opposite ends of a tiny sensor.

On the sensor, the light signals of each half-disk are converted to electrical signals and then compared. If the signals are not precisely equal, this means that the roof-prism is not splitting the image precisely in half. The telescope is then adjusted until the signals are equal and the image is split right down the middle. When this is accomplished in both sensors for each axis (x- and y-axes), then the telescope is focused on the exact center of the guide star.



For more information, comments or questions, contact GP-B at www@relgyro.stanford.edu or visit http://einstein.stanford.edu/

Focusing On the Guide Star